Dynamics of the Quiet Polar Cap

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Work in the past has established that a few percent of the time, under northward interplanetary magnetic field and thus magnetically quiet conditions, sun aligned arcs are found in the polar cap with intensities greater than the order of a kilo Rayleigh in the visible. Here we extend this view. We first note that imaging systems with sensitivity down to tens of Rayleighs in the visible find sun aligned arcs in the polar cap far more often, closer to half the time than a few percent. Furthermore, these sun aligned arcs have simple electrodynamics. They mark boundaries between rapid antisunward flow of ionospheric plasma on their dawn side and significantly slower flow, or even sunward flow, on their dusk side. Since the sun aligned arcs are typically the order of 1000 km to transpolar in the sun-earth direction, and the order of 100 km or less in the dawn-dusk direction, they demarcate lines of strongly anisotropic ionospheric flow shears or convection cells. The very quiet polar cap (strongly northward IMF) is in fact characterized by the presence of sun aligned arcs and multiple highly anisotropic ionospheric flow shears. Sensitive optical images are a valuable diagnostic with which to study polar ionospheric convection under these poorly understood conditions.
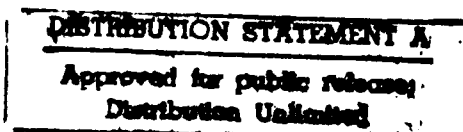
1. Introduction

The intent of this paper is to make three points.

1) Sun aligned arcs are not a rare curiosity, rather, they are prevalent in the polar cap half the time (occurring when the interplanetary magnetic field IMF is northward).

2) Sun aligned arcs are signatures of sharp slowing (or even reversal) of antisunward ionospheric plasma flow; they have simple arc electrodynamics.

3) Sun aligned arcs are thereby a most valuable tool for discovery and definition of the character of polar cap convection for northward IMF conditions, i.e., the half of the time about which convection is very poorly understood.

2. Occurrence of Sun Aligned Arcs

The view of the polar regions shown in Fig. 1 (AKASOFU, 1976), as seen in optical or auroral emission features, has served us well as a frame of reference for polar research for fifteen years, and continues to do so.

For about as many years, sun aligned arcs have also been known to occur deep within the polar cap, in the blank area of Fig. 1 roughly poleward of 75° latitude (in geomagnetic coordinates), when the interplanetary magnetic field (IMF) is northward (BERKEY et al., 1976; ISMAIL et al., 1977; LASSEN and DANIELSEN, 1978), as for example in Fig. 2. These and more recent studies (e.g. examples to be found in GUSSENHOVEN,

90 09 04 065

CUSP REGION

12

60°

POLAR CAP

DIFFUSE AURORAL
PATCHES AND
MANTLE AURORA

80°

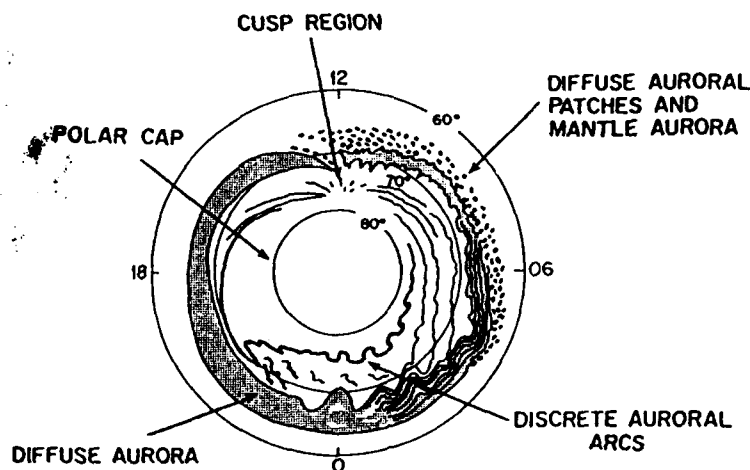18

06

DISCRETE AURORAL
ARCS

DIFFUSE AURORA

0

Fig. 1.   Schematic diagram showing the different particle precipitation regions in the auroral oval. From Akasofu (1976).

1982) have all described these sun aligned arcs as present in the polar cap only a few percent of the time.

Dramatic views of the polar cap from the Dynamics Explorer satellite have called attention to bright wide long lived sun aligned arcs that connect from the day to the night side auroral oval to form an emission feature resembling the greek letter theta. These, described in considerable detail (FRANK et al., 1986), are also present a very small fraction of the time. Speculation on the responsible mechanisms up until this time have included special magnetospheric topological conditions relative to the IMF, also thought to occur only occasionally.

The first finding to be emphasized here is that polar cap sun aligned arcs occur about 50% of the time, not a few % of the time. As such they represent the normal state of the northward IMF central polar, not an occasional curiosity. As such they will be seen to take on much more significance than previously recognized. To pursue this, it is necessary to show consistency of this view with the prior work just cited, and clarify the definition of sun aligned arc.

All sky imaging photometers with sensitivities down to some tens of Rayleighs, through use of image intensifiers, have observed sun aligned arcs deep within the polar cap, initially at Thule, Greenland (WEBER and BUCHAU, 1981) and subsequently more extensively at Qaanaaq and Sondrestromfjord, Greenland and Svalbard (CARLSON et al., 1984, 1988).

Examination of the data from this net of polar imagers shows that in the central polar cap (Qaanaaq and Thule), sun aligned arcs are visible in 6300A emission roughly half the time (with intensities near or exceeding some tens of Rayleighs), generally when conditions are quiet and the IMF presumably northward. These are attributed to weak fluxes of soft (order 100 eV or less) particles. Less often, coincident with the relatively stronger 6300A arcs, sun aligned arcs are also seen in the 4278A images. These are also attributed to weak fluxes of soft particles (ratios of 6300A to 4278A exceeding 10 to 1 and 4278A emissions near or below order 10R) (CARLSON et al., 1984). Still less often
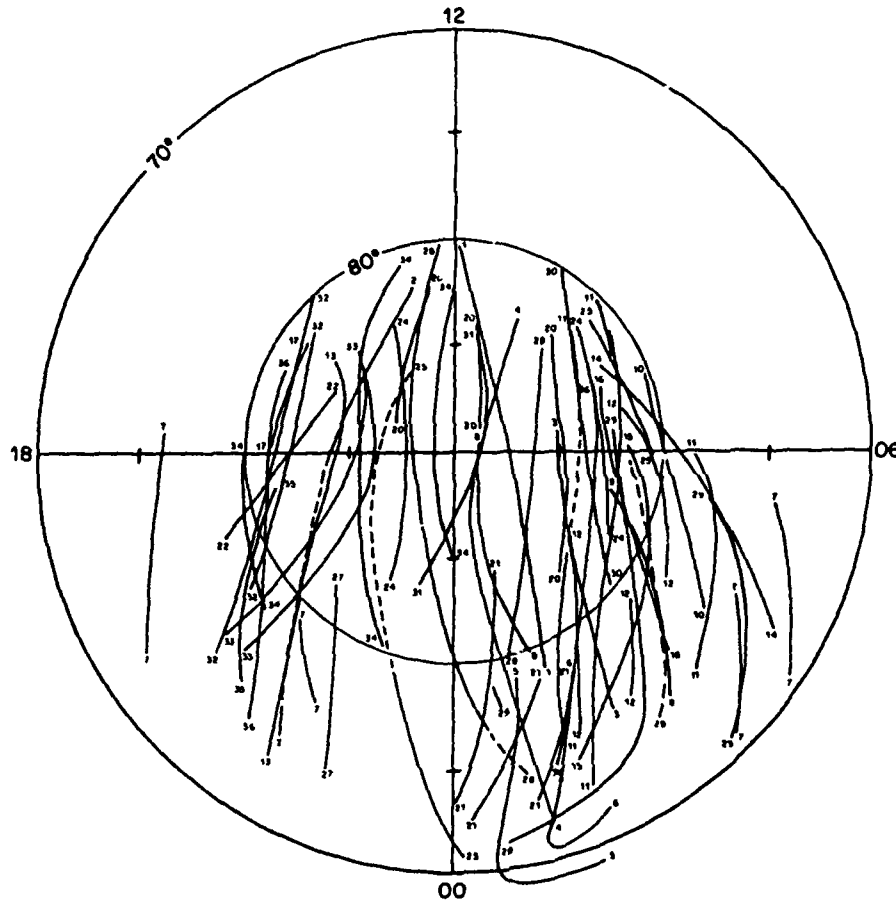
Fig. 2.   The observed position of the bright sun-aligned arcs in the northern polar cap plotted on a corrected
geomagnetic latitude-time grid. From ISMAIL et al. (1977).

occasional intense sun aligned arcs are seen, producing significant E region ionization,
attributed to more intense fluxes of harder particles.

Consistency with previously published work can then be easily understood in terms
of sensitivity threshold. Previous work, with imagers over an order of magnitude less
sensitive, had such a high threshold of sensitivity that it saw only the brightest sun aligned
arcs. The image intensified ASIP's literally let us look at the polar cap with new eyes, and
let us see the much more common weaker sun aligned arcs.

Let us clarify at this point that here and in the following, reference to sun aligned
arcs as seen on the ASIP's is confined to that class of arcs which are: stable in time,
extended in space, and parallel to the direction from the earth to the sun. Note that for
near earth satellites if line scanning photometers are to be able to track transpolar arcs
over 20° of latitude, as DMSP or the ISIS II data of Fig. 2, the arc must be stable for at
least 5 minutes. In fact, persistence in our ASIP fields of view typically well exceeds this,
and can last for over an hour (e.g. Fig. 3). The spacial extent typically exceeds 1000 km,

Fig. 3. Weak stable extended 6300Å sun-aligned arcs, persisting over an hour (the bright spots on the edge of the field of view are lights near the horizon).

the diameter of the ASIP field of view for F region optical emissions, since very rarely is a sun aligned arc seen to terminate part way across an image. By combining pairs of sun aligned ASIP images, we can infer a spacial extent in excess of 2000 km (e.g. Fig. 4). More definitive findings will be possible in the future now that AFGL has added Norde, Greenland ASIP coverage (Winter 1990-1991) to the transpolar net from Qaanaaq to Svalbard (operated cooperatively with the Danish Meteorological Institute for Greenland and the University of Oslo for Svalbard). Connection to the day and night side auroral oval, as might be inferred from analogy to theta aurora geometry, is found at Svalbard and Sondrestromfjord, but statistics of occurrence have not yet been extracted from available data.

In addition to single sun aligned arcs illustrated in Figs. 3 and 4, it is common to find multiple arcs, as illustrated in Fig. 7(a).
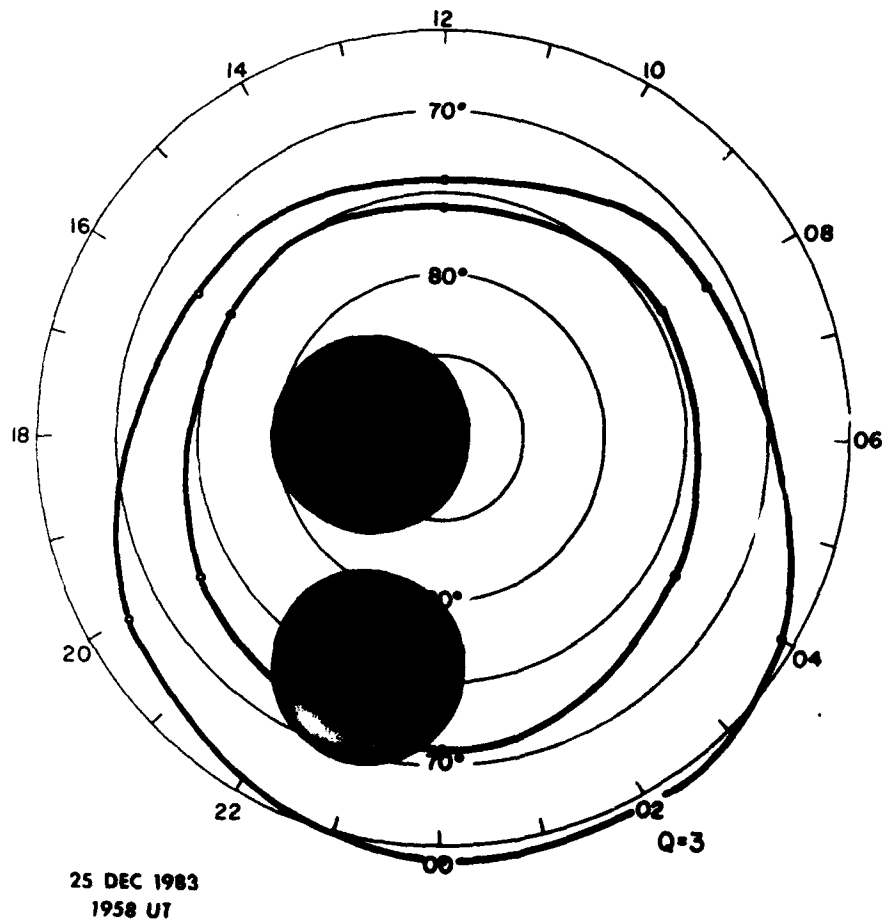

Fig. 4. An example of a sun-aligned arc, connected to the premidnight auroral oval, extending over 2000 km sunward as seen in a pair of 6300A all sky imaging photometers.

3. Sun Aligned Arc Electrodynamics

A simple electrodynamics situation that leads to an optical arc signature along a boundary line is illustrated in Fig. 5 (e.g. see REIFF and BURCH, 1985).

Consider initially uniform conductivity across the boundary. A plasma velocity reversal (left-hand side) or velocity gradient (right-hand side) cross the boundary line, and the equivalent horizontal electric field differential, would produce a horizontal pedersen current convergence at the boundary in the absence of a verticle current component. Thus, a verticle (actually magnetic field aligned) current flows, with that magnitude required to maintain a divergence free current state.

Up to this point in the description the only difference between the left hand shear reversal and the right hand shear differential flow is the rest frame velocity from which the flow is viewed. Of significance, it is the rest frame of the neutral gas that determines the currents. The need to operate in the neutral gas rest frame may be understood in part by recalling that it is collisions between the charged and neutral gas particles, and in particular different collision frequencies (mobilities) of the ions vs electrons with the neutral gas particles which produce a finite conductivity and pedersen current perpendicular to the velocity shear boundary.

The sense of the velocity difference across the boundary determines whether it tends to drive a horizontal convergence or divergence, and thus requires a vertically upward or downward current to maintain a divergence free state. In Fig. 5 the sense leads to an upward current, presumably carried into the ionosphere by a flux of downcoming suprathermal electrons.

Note that if a series of velocity differentials occur, alternatively reversing (plasma alternately speeding up then slowing), the upward current sheets will alternate with intervening downward current sheets along velocity difference boundary lines. These downward current sheets will presumably be carried by upgoing thermal electrons.

VELOCITY SHEAR &
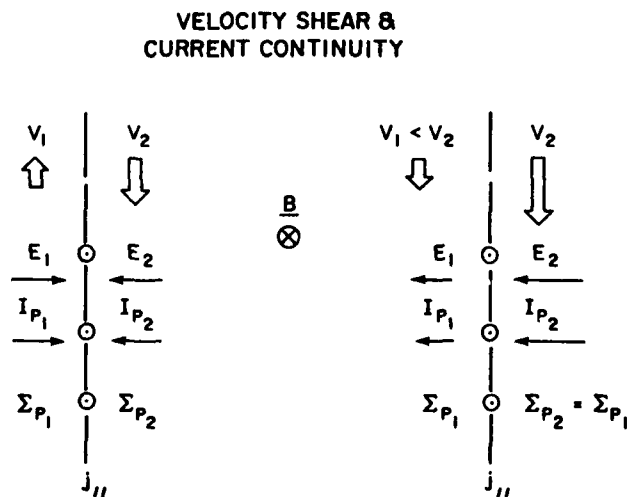**CURRENT CONTINUITY**

Fig. 5.   Two examples of a simple electrodynamic situation that would produce a sun-aligned arc.

This simple arc electrodynamics, as discussed by LYONS (1980), is in fact the electrodynamics that pertains to (stable in time, extensive in sunward direction) sun aligned arcs (CARLSON et al., 1988). We should note that, as indicated on the left-hand side of Fig. 5, a change in conductivity alone across the boundary could lead to this same circuitry, in the absence of a velocity shear. We have found no examples of this alone creating sun aligned arcs.

Since the current carriers of the "vertical" (actually, magnetic field aligned) current are supra thermal electrons with energies of tens of eV or greater, they should produce impact excitation of optical emissions, providing the optical signature of the arc. They by the same token will be expected to produce impact ionization, thereby enhancing the conductivity within the arc, and modifying the distribution of currents that flow within the arc itself. This feedback effect must be allowed for in any detailed self consistent treatment of the circuitry of the arc. This will be treated in a more detailed study.

Here our main point is that the sun aligned arcs are visual markers of velocity shear lines, lines of sharp velocity differentials, of a specific sense: greater antisunward velocity on the dawn side than the dusk side of a polar cap sun aligned arc. Thus one is to look at sun aligned arcs with new eyes (literally with ASIP's, figuratively with this simple arc electrodynamics in mind) as regards polar ionospheric convection. This view is simply as indicated in the cartoon Fig. 6.

Coincident satellite in situ and ground based ASIP data used to verify (CARLSON et al., 1988) this finding are shown in Fig. 7. The two brightest sun aligned arcs are labeled ARC A and ARC B, seen as two clearly visible bright streaks in the image (6300A sun aligned arcs) in Fig. 7(a) coincide with the magnetic field aligned projection of the two strongest energetic electron flux enhancements within the polar cap in Fig. 7(b). The auroral electron flux ends abruptly at the poleward edge at about 79° magnetic invariant latitude (ILAT). The two strongest electron flux enhancements, peaking near 85° and 86.5° ILAT, are deep within the polar cap, as determined by the in situ particle population measurements (and consistent with the ASIP data).

Our main focus here however is the gradient of the plasma drift velocity component in the sunward/antisunward direction, shown in Fig. 7(d). The two sun aligned arcs coincide in space and time with the steep gradient in antisunward velocity. The 6300 electron impact component, and simultaneously measured incident electron flux enhance-
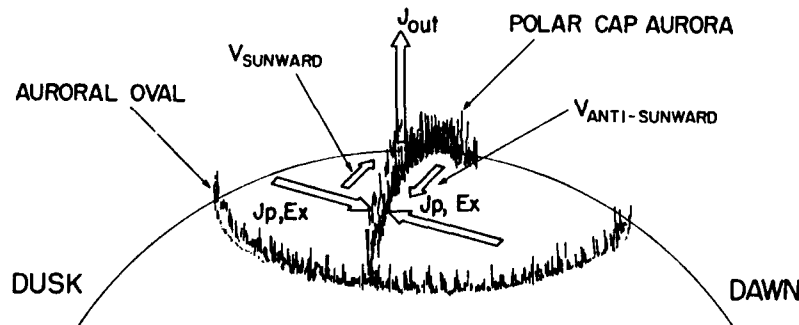

Fig. 6. Cartoon representation of the simple electrodynamics characteristic of stronger sun-aligned arcs. The plasma flow on the dusk side (slower than the dawn side) may actually be antisunward, stagnant, or sunward, for a range of arc intensities.
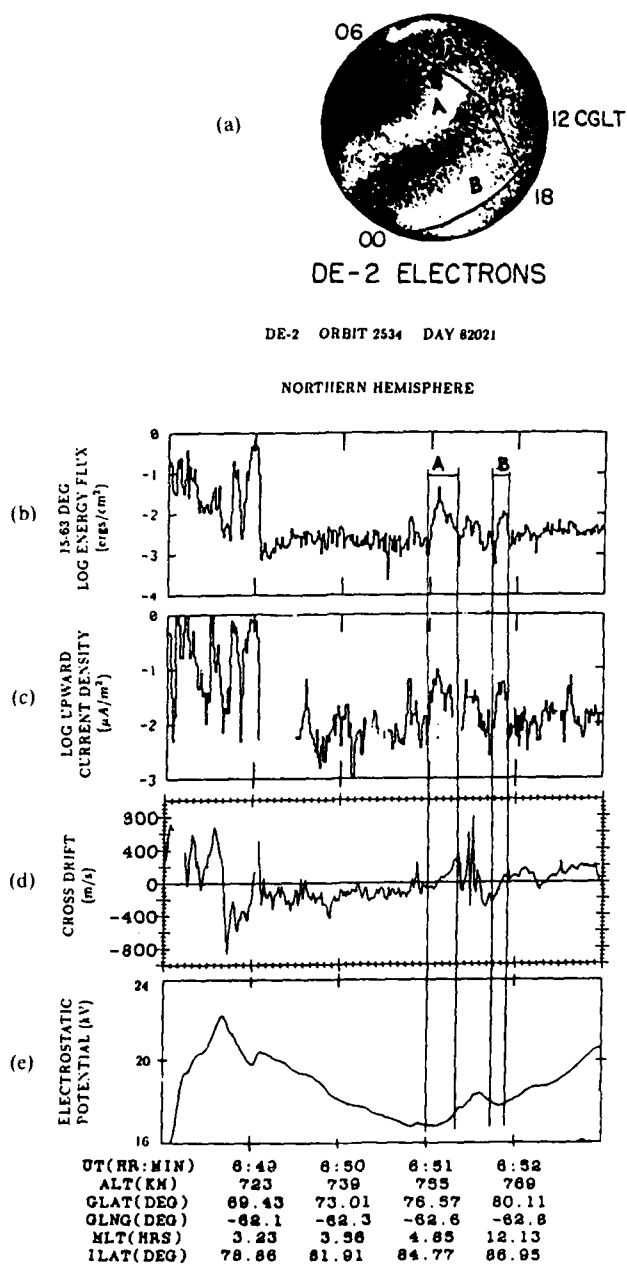
(a)

DE-2 ELECTRONS

DE-2   ORBIT 2534   DAY 82021

NORTHERN HEMISPHERE

UT(HR:MIN)	6:49	6:50	6:51	6:52
ALT(KM)	723	739	755	769
GLAT(DEG)	69.43	73.01	76.57	80.11
GLNG(DEG)	-62.1	-62.3	-62.6	-62.8
MLT(HRS)	3.23	3.56	4.85	12.13
ILAT(DEG)	78.86	81.91	84.77	86.95

Fig. 7. (a) The image of polar cap emissions from ASIP, taken during the passage of the DE 2 spacecraft
through the field of view. The numbers 1 7 indicate the mapped position of the satellite at 30-s intervals
starting at 06:49:30 UT. (b) (e) Electrodynamic parameters measured by DE 2 during the overpass shown
in Fig. 7(a) 04-12 CGLT. The top two panels show the integrated electron energy flux and field-aligned
current, respectively, provided by the precipitating electrons. The lower two panels show the component of
the ion drift perpendicular to the satellite track and the electrostatic potential distribution along the track,
respectively. The locations of two discrete emission features seen in Fig. 7(a) are labeled A, B. From
CARLSON et al. (1988).

ment, both begin where the antisunward velocity begins to decrease (in the earth-sun frame of reference), and end where the antisunward velocity component stops decreasing (and may begin to increase again). This is true for both clearly visible arcs in the ASIP.

This correspondence between velocity gradient and enhanced electron flux is seen for several other electron flux enhancements in Fig. 7(b) within the polar cap. We might reasonably speculate from this similar electrodynamic correlation that these features may also be sun aligned arcs. However, without simultaneous ASIP data we do not know the horizontal extent of these electrodynamic features across the one-dimensional sub-orbital satellite track, and cannot know that they are sun aligned arcs.

If it were possible to measure electric fields, or plasma flow patterns, over a large horizontal area, this could provide an important independent verification of this description, as well as an important diagnostic tool. In fact, there is a way to map horizontal two-dimensional plasma flow fields: using an incoherent scatter radar. An example of such data collected by the Sondrestromfjord ISR is shown in Fig. 8. This data was collected by scanning the azimuth of the radar in a full circle at a fixed 45 degree elevation, and then projecting the data on this conical surface down onto a horizontal plane. Wherever the electron density is sufficiently great to give a useful radar echo, data is obtained; where no data is shown the electron density is below the lowest density contour shown $(4 \times 10^4$ electrons/cm$^3)$. The contours are of electron density in uniform steps of 0.2 from 0.4 to 1.4×10^5 cm^3. The radial lines are line of sight ionospheric plasma velocities, for the most part away from the direction of the sun, with a scale as shown in the figure. The circular feet of the radial lines identify the location at which the velocity component was measured.

The chemical lifetime of ionization below 200 km is so short that for this stable electron density feature, observed to persist for over ten minutes in a stable configuration and location, we must recognize this as a region of stable ongoing production of ionization, by a flux of energetic particles. Thus we must further conclude that this stable feature would be seen in optical impact excitation as well, i.e. as a stable auroral arc.

If the simple electrodynamics we have described applies to this arc, we can examine the flow vector data (Fig. 8(a)) to determine where we expect to find the incoming flux of enhanced ionizing energetic particles, i.e. the enhanced electron density contours below 200 km altitude. This means going through the plasma flow vector data, point by point, to identify where successive vectors show a slowing of antisunward velocity, vs constant or increasing velocity in going in the direction from dawn towards dusk in the earth-sun frame of reference. The pair of lines so determined for the 170 km altitude as shown in Fig. 8(a) for the velocity data, are repeated in Fig. 8(b) where they are found to be in excellent agreement with the expectations of a simple electrodynamic arc in that they very well bracket the contours of enhanced electron density.

The arc in this case is for a quiet, stable, dawn auroral oval location, over Sondrestromfjord near 06:00 local time. Such electrodynamics for a sun aligned arc closer to local midnight at the same location, and clearly within the polar cap as based on optical images, is shown in Fig. 9. The same evaluation as for Fig. 8 applies here again.

The arguments put forth here for the data of Figs. 7, 8, 9, while rather precise as regards spacial and temporal coincidence of arcs with electric field and velocity gradients of the right sign, have not been discussed here quantitatively with respect to the magnitude of the current and its continuity. Calculations of horizontal conductivities and currents, and vertical currents can be done. The results of such calculations have been
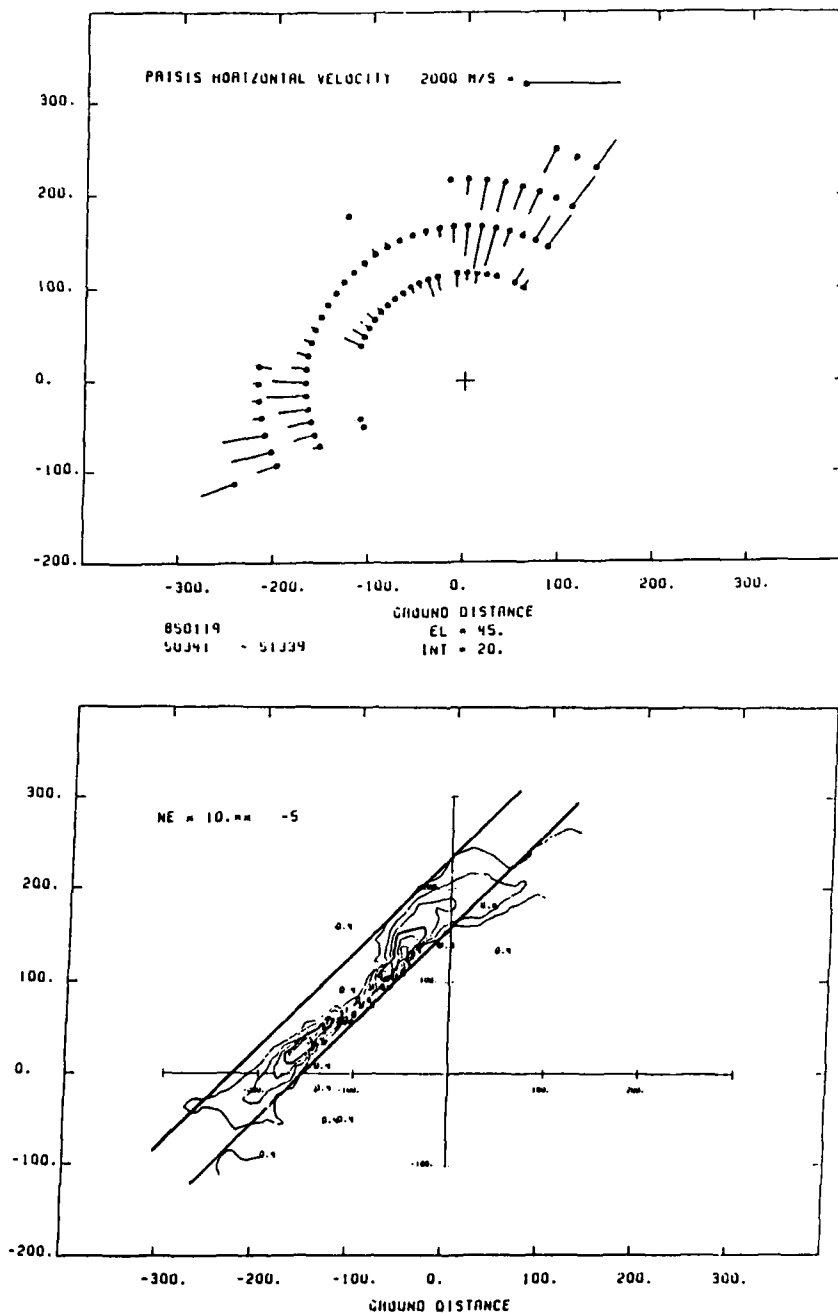
Fig. 8. Sondrestromfjord incoherent scatter radar (ISR) data in the dawn auroral oval. (a) Line of sight plasma velocities, ranging from 1 km/sec antisunward to 1 km/sec in the extreem northeast. (b) Electron density contours (0.4 to 1.4×10^5 cm^{-1}) measured at same time. The parallel pair of lines bracket the 40 km region over which the 170 km altitude antisunward plasma flow decreases in the dawn to dusk direction. They show that the ongoing ionization production coincides very closely with the simple arc electrodynamics view.
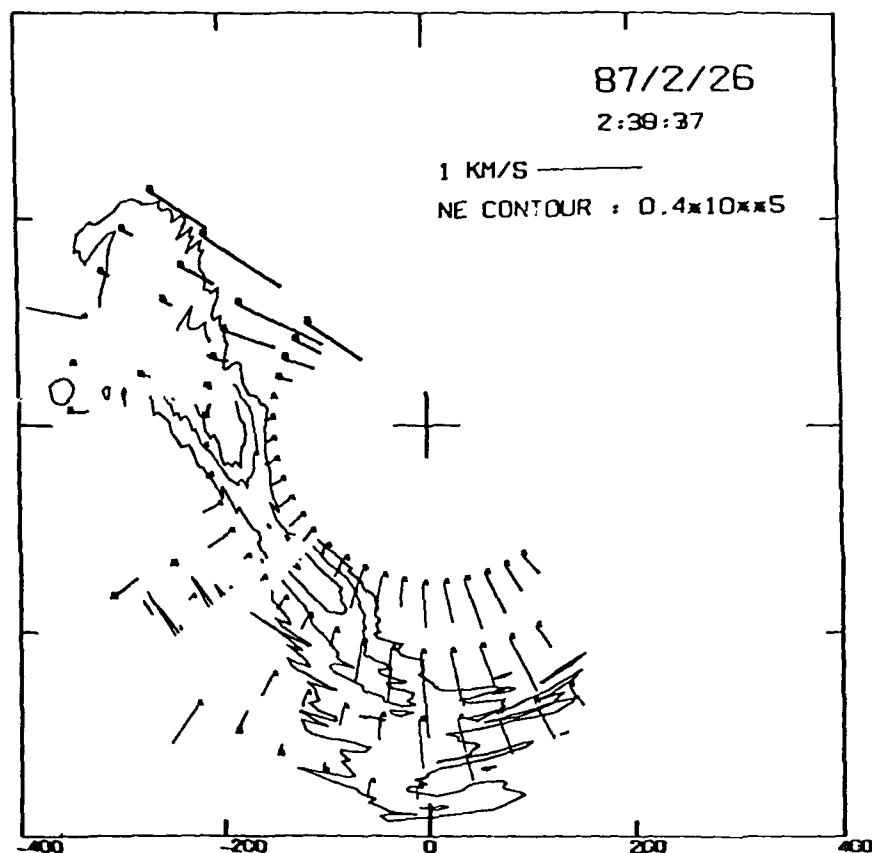
Fig. 9.   Line of sight plasma velocities and electron density contour (0.4 to 1.2 × 10⁵ cm⁻¹) for 02:30 02:37 UT February 26, 1987. This sun aligned arc, near midnight local time at the Sondrestromfjord ISR in Greenland, shows the ISR capability to measure plasma flow (and thus electric field) over mesoscale areas (hundreds of km square). The electron density enhancement, produced below 200 km by ongoing electron impact ionization, coincides again here with the plasmadrift (electric field) gradient of the sign leading to an upward current (downcoming electrons) out of the arc.

reported by CARLSON *et al.* (1988), who quantitatively substantiate these findings.

Based on a large number of arcs so investigated we conclude that stable, spatially extended, sun aligned arcs in the polar cap (and numerous other arcs as well) have the simple arc electrodynamics illustrated in Fig. 5.

4.   Applications to Polar Convection

Over the past 20 years a great deal of knowledge has been developed as to the polar ionospheric convection, and its vector interplanetary magnetic field (IMF) dependence for southward IMF conditions, a condition that prevails about half of the time. However, very little is known about convection during the other half of the time, when the IMF is northward.

It follows rather directly from the discussions above that stable polar cap sun aligned

arcs can serve as a very valuable diagnostic in developing better definition and understanding of polar ionospheric convection for northward IMF conditions.

Consider transpolar horizontal ionospheric flow velocity measured across the orbital track by a polar orbiting satellite. This measurement can be expressed as well as the equivalent electric field normal to both the plasma flow and the magnetic field. Integrating this electric field along the orbital track provides a measure of the potential drop across the polar cap and, more importantly here, the electrostatic potential distribution within the polar cap along the orbital trajectory. Since plasma flow is along lines of equipotential, these can be used to begin to generate a polar convection pattern.

If the polar convection pattern were invariant, a large number of different orbital passes could be combined to define the two-dimensional potential distribution and convection patterns. If the convection is large scale, changes slowly, and is repeatable based on a modest number of measurable parameters (e.g. the relative magnitude and sign of the IMF) this procedure can still apply. This procedure has been found to work well for southward IMF, as a basis for refined IMF dependencies of a two cell convection pattern (e.g. HEELIS, 1984).

For northward IMF the dominant character of the cross track plasma flow deep within the polar cap has been viewed as irregular, highly structured, or even "turbulent" (see e.g. poleward of about 80° magnetic latitude in Fig. 10, which corresponds to the
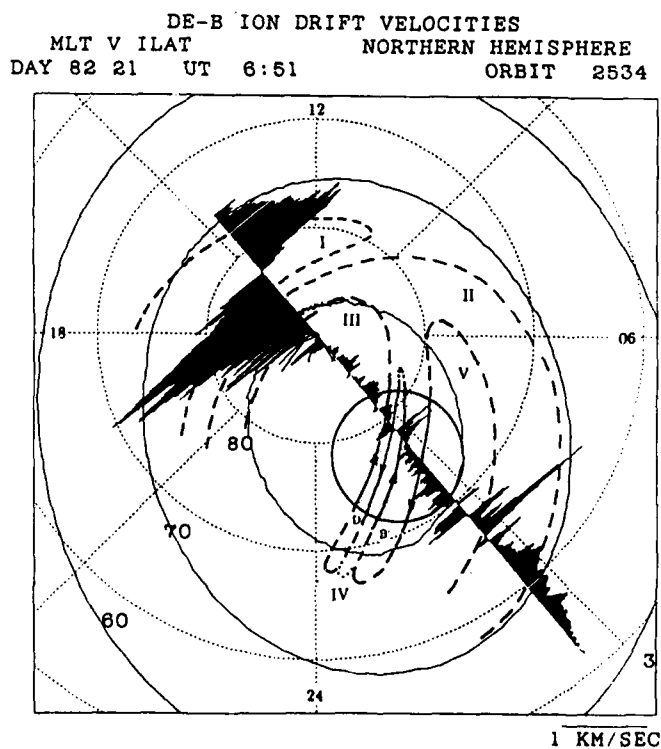

Fig. 10.   An implied convection pattern consistent with observed optical emissions and plasma convection velocities measured by DE 2. The flow lines describing cells III, IV, and V are at the same potential and may be connected "finders" or separate convection cells. From CARLSON et al. (1988).

data of Fig. 7). With no guidance as to either the off-track spacial scale or the temporal scale over which this velocity structure changes, very little could be deduced about the associated convection; very little has been.

However, within the field of view of the ASIP all sky imager (shown as the 1000 km diameter circle in Fig. 10), we know that the two cross track velocity shears discussed in Fig. 7 extends in the earth-sun direction spanning a distance of at least 1000 km cross track. Furthermore, the spacial and temporal coherence of the arcs seen in the ASIP imply a similar coherence in the velocity shears and convection features. Further, since plasma flow is along lines of equiptional, plasma crossing the orbital track at a given electrostatic potential value will follow a path that crosses the orbital track elsewhere at that same potential.

The dashed lines in Fig. 10 show one possible convection pattern corresponding to the data of this orbit. Within the field of view of the ASIP the convection line can be drawn with confidence, and is shown with a solid line. Beyond the ASIP field of view there is ambiguity. Multiple points of the same potential along the orbital track mean multiple possible return paths for the convection flow.

A more complete coverage of the polar cap with ASIP's would reduce this ambiguity, and better define these mesoscale shears, or gradient lines, and structured convection for northward IMF.

For the combined ASIP and satellite coverage analyzed in this way to date we have already discovered that, far from "turbulent", the northward IMF polar convection is highly ordered (CARLSON et al., 1988). It exhibits highly anisotropic structure with spacial coherence over distances of 1000 to several thousand km in the sun aligned direction. Furthermore, this spacial coherence persists with a temporal coherence of minutes to an hour or longer. Very ordered mesoscale convection exists, with multiple cells or "fingers" of reduced antisunward flow.

We have now established a more extensive network of ASIP's (Qaanaaq, Nord, Sondrestromfjord, Greenland, and Svalbard), in collaboration with the Danish Meteorological Institute and Prof. Alv Egeland at the University of Oslo, covering a substantial fraction of the polar cap. These, combined with transpolar satellite measurements of plasma drift, should allow significant advances in defining and understanding polar ionospheric convection for northward IMF conditions, as well as its implications for associated magnetospheric topology.

5. Conclusion

Sun aligned arcs are common in the polar cap, found roughly that half of the time when the IMF is northward. These arcs, stable in time, extended in the sunward direction, have simple electrodynamics and as such visually mark lines of sharp plasma flow gradients or shears. In combination with polar orbiting satellites or ground based radars (or future upgraded Fabry Perot interferometers) measuring plasma flow or electric field vectors, ASIP's can be a very valuable diagnostic tool for defining and understanding northward IMF polar ionospheric convection, and associated magnetospheric topology.

radar. Dynamics Explorer B satellite, and AFGL all sky Imaging Photometer (ASIP), collected in Greenland with help from the Danish Meteorological Institute, with approval from the Danish Commission for Scientific Research in Greenland.

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